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# 85 $\mu\text{m}$ core rod fiber amplifier delivering 350 W/m

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## ABSTRACT

An improved version of the distributed modal filtering (DMF) rod fiber is tested in a high power setup delivering 350 W/m of extracted signal average power limited by the available pump power. The rod fiber is thoroughly tested to record the transverse modal instability (TMI) behavior and also measure degradation of the TMI threshold with operation time due to induced absorption in the active material increasing the thermo-optical heat load. Multiple testing degrades the rod fiber and TMI threshold from >360 W to a saturated power level of roughly 240 W.

**Keywords:** Fiber optics amplifiers and oscillators; Lasers, Fiber; Thermal effects.

## 1. INTRODUCTION

Ytterbium-doped silica based fiber lasers and amplifiers can generate megawatts of peak power and hundreds of watts in average power using direct amplification. High pulse energies and peak powers require large mode area (LMA) fibers,<sup>1-4</sup> and as these fiber amplifiers can extract 100s of Watts per unit length, thermal-optic effects causing a thermally induced refractive index increment significantly influences the waveguiding mechanisms.<sup>5-7</sup> The index perturbations can cause very LMA fibers to support higher order modes (HOMs) at high power operation which can lead to mode degradation, and eventually transverse mode instability (TMI) that sets in at a system and fiber dependent average power threshold.<sup>2,8-11</sup> TMI results in rapid beam fluctuations, where the initially Gaussian like mode profile starts to fluctuate as TMIs set in, typically between the fundamental (FM) and the first higher order mode (HOM). This significantly degrades beam quality and constitutes an impediment to future power scaling. TMIs are often the first nonlinear effect to set in for very LMA fibers in high power amplifier and laser systems. Thus understanding the origin and mechanisms behind are important for future mitigation strategies. High power operations of rod fiber amplifiers cause the TMI threshold to degrade with operation time,<sup>2,11,12</sup> since TMIs are highly dependent on the thermal heat load generated in the core due to the quantum defect between signal and pump wavelength and also photodarkening of the active material.

In this work we test an improved version of the distributed modal filtering (DMF) rod fiber in a high power setup delivering 350 W/m of stable extracted signal power limited by the available pump power. To our knowledge, this is the highest achieved stable average output power from a 1 m rod fiber amplifier, and an increase of 25 % compared with the first generation DMF rod fiber.<sup>2</sup> The improved DMF rod fiber is thoroughly tested to record the TMI behavior and also measure degradation of the TMI threshold by accelerating the induced photodarkening. These tests reveal that the TMI threshold saturates at roughly 240 W of signal average power.

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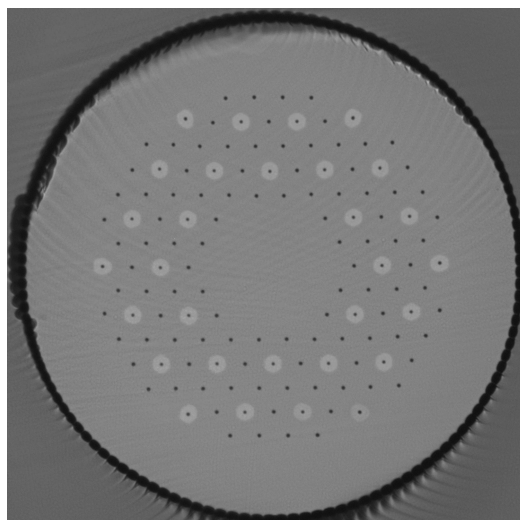


Figure 1. Cross section of the improved version of the DMF rod fiber. The DMF rod fiber has an  $85\ \mu\text{m}$  core and a  $260\ \mu\text{m}$  pump air cladding. Resonant high index DMF elements in the inner cladding ensures SM operation both passively and at high average power levels.

## 2. 350 W/M EXTRACTED STABLE SIGNAL POWER FROM DMF ROD FIBER

A new version of the DMF rod fiber is experimentally tested in a high power setup. The rod fiber has an  $85\ \mu\text{m}$  core, a  $260\ \mu\text{m}$  pump air cladding, and a length of 1 m, see rod fiber cross section in Fig. 1. It is endcapped with anti-reflection (AR) coated endcaps, where one has a  $2^\circ$  angle. The core is Ytterbium doped and the pump absorption is 18 dB/m. Resonant high index DMF elements are placed in the inner cladding effectively coupling with the HOM ensuring single mode (SM) operation of this very LMA fiber design.<sup>1,13</sup> The DMF rod fiber is resilient to large thermal loads due to these resonant inclusions. The thermo-optic effect is a non local effect that cause the entire rod fiber to heat up when operated at high average power. The heat load gradient perturbs the waveguiding properties increasing the effective refractive index. The core's and also the DMF element's refractive index increases, and ensure SM operation even for large heat loads at high average power levels, where standard PCF fibers become multi mode (MM).<sup>15</sup>

The high power single pass setup consists of a 1032 nm fiber based ps seed at 40 MHz repetition rate giving 10 W of seed power, and a 976 nm fiber coupled diode pump delivering up to 550 W.<sup>2</sup> The output signal

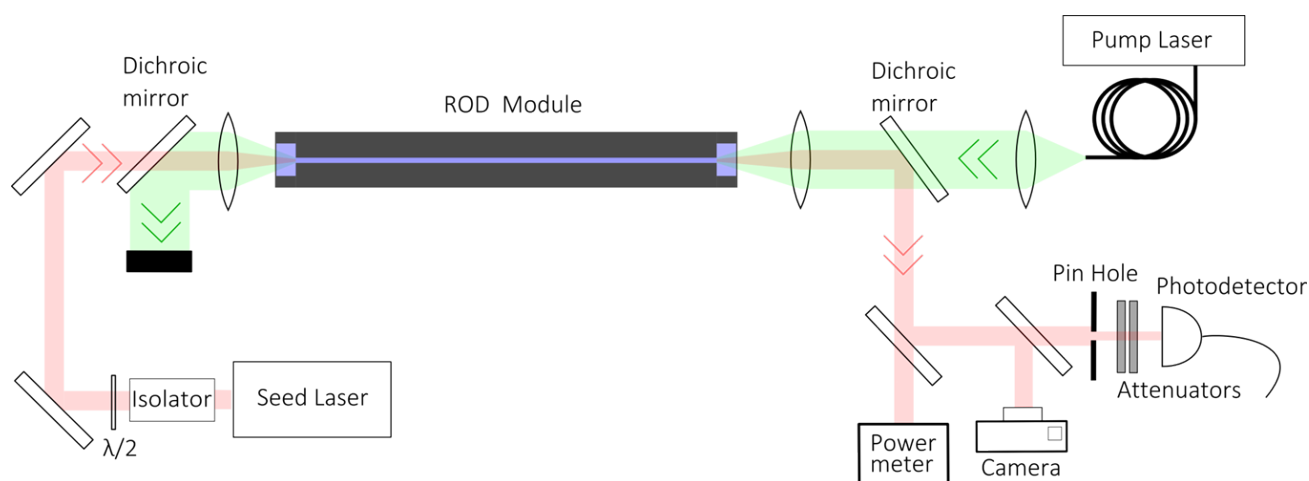


Figure 2. High power single pass setup with a 1032 nm fiber based ps seed at 40 MHz repetition rate giving 10 W of seed power, and a 976 nm fiber coupled diode pump delivering up to 550 W.

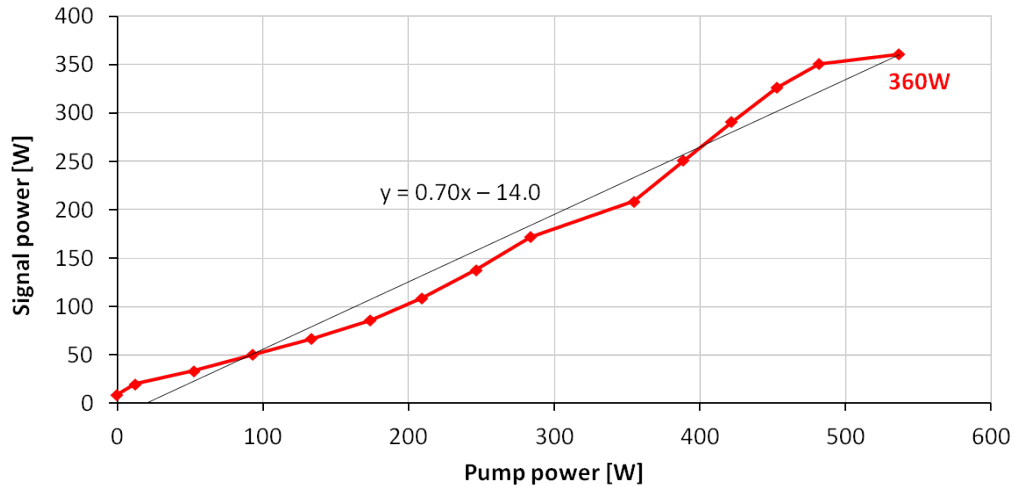


Figure 3. Signal average power as a function of coupled pump power for the improved version of the DMF rod fiber yielding a maximum stable output of 360 W without any transverse modal instabilities.

power is measured using a dichroic mirror to reflect the signal to the power meter and a beam splitter for beam diagnostics, see setup in Fig. 2. TMIs are measured with a simple measurement technique by having a pinhole in front of a photodetector<sup>14</sup> and processing the signal with an oscilloscope. The AC photodiode signal remains small with temporarily stable output i.e. operation in the FM, but increases when TMI sets in.<sup>11</sup>

360 W of stable signal average power is achieved from the DMF rod fiber with the maximum 550 W of pump power in the first test run. This corresponds to 350 W/m of extracted stable signal average power. Due to a limit in available pump power it was not possible to reach higher power levels and the threshold for TMI. The signal average power as function of coupled pump power is plotted in Fig. 3. The slope efficiency is 70 % and a maximum of 71 % of optical to optical efficiency is achieved. Previously, the first generation DMF rod fiber was tested experimentally in the same setup delivering 292 W/m signal average power with 15 W seed by Laurila et al. in Ref. 2. The increase in extracted output power is 25 %, when comparing the improved DMF rod fiber to the first generation. The first generation DMF rod fiber was operated in the leaky regime, whereas the improved DMF rod fiber is operated in the guiding regime, resulting in higher core confinement and improved beam quality, and ease rod fiber handling.

### 3. SATURATION OF TRANSVERSE MODAL INSTABILITY THRESHOLD

The DMF rod fiber is further tested to investigate TMI. TMIs are highly dependent on the thermal heat load generated in the core due to the quantum defect between signal and pump wavelength and also photodarkening of the active material.<sup>2,11,12</sup> In our experiments, the photodarkening process is accelerated by pumping the DMF rod fiber with 200 W without any seed light for 1 h to achieve maximum population inversion yielding amplified spontaneous emission (ASE), denoted an ASE test. This will enhance the color center creation and absorption of the active material yielding an increased heat load. After this another test to find the TMI threshold is



Figure 4. The initial test procedure consists of 20 tests, where one test include a TMI test and one ASE test, performed on the DMF rod fiber.

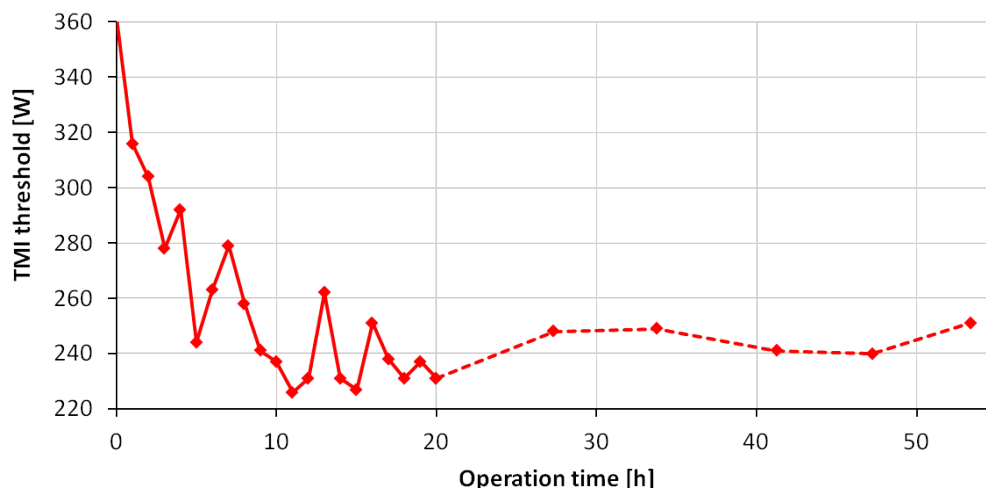


Figure 5. Degradation of the TMI threshold with operation time for the improved version of the DMF rod fiber. The solid line corresponds to 20 TMI and ASE tests, and the dashed line corresponds to 5 TMI and amplifier tests. The TMI threshold power level is initially above 360 W and degrades to roughly 240 W.

performed with 10 W seed power, denoted a TMI test. Where after another ASE test is performed. This test procedure is repeated 20 times, see Fig. 4 for a schematic overview, and will degrade the DMF rod fiber resulting in a saturated power level of the TMI threshold.

After the first ASE test a second TMI test is performed and reveals a TMI threshold of 316 W measured with a photodetector and oscilloscope as described in Sec. 2. The test procedure of 20 TMI and ASE tests is performed and the TMI threshold as a function of operation time is plotted as the solid line in Fig. 5. It is obvious that the threshold degrades with the number of tests, especially for the first 5 tests, where after the slope decreases and it appears as the TMI threshold has saturated to a power level of roughly 240 W.

In order to verify that the TMI threshold has saturated the DMF rod fiber is operated as an amplifier, i.e. as intended for industrial use, delivering 200 W of signal average power for 6 h - 8 h, denoted an amplifier test. Where after the TMI threshold is recorded again. A schematic overview of this following test procedure that is repeated 5 times is seen in Fig. 6.

The DMF rod fiber delivers 200 W of stable signal average power during the amplifier tests with no observations of TMI. After each amplifier test a TMI test is performed and reveal TMI thresholds of 240 W - 250 W, clearly indicating that the TMI threshold has saturated without any further decrease in threshold. The results are plotted in Fig. 5 as the dashed line.

The overall degradation of TMI threshold is roughly 33 %. However no significant degradation in optical efficiency is observed. This indicates that minor degradation of a fiber optical amplifier (FOA), usually observed under the normal burn-in procedure, with minor induced photodarkening absorption due to color center creation, can have large impact on the generated heat load within the FOA. Typical very LMA FOAs rely on very small index steps between core and cladding, which makes them sensitive to the small waveguide perturbations caused



Figure 6. The following test procedure consists of 5 tests each including a TMI test and an amplifier test, where the DMF rod fiber is operated as an amplifier delivering 200 W of signal average power for 6 h - 8 h.

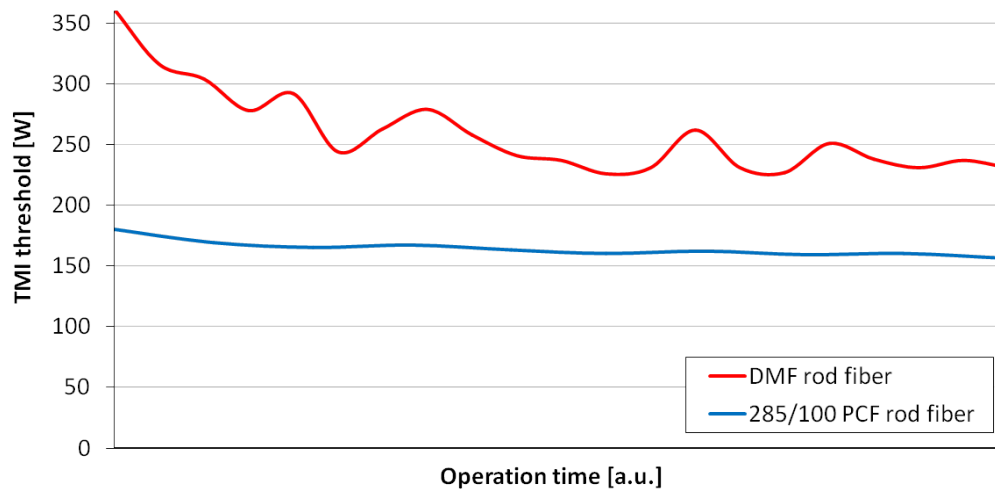


Figure 7. Degradation of the TMI threshold with operation time for the improved version of the DMF rod fiber and a 285/100 PCF rod fiber.<sup>11</sup>

by for instance bending or heat loads through the thermo-optic effect.<sup>14,15</sup> The quantum defect results in a heat load of approximately 6 %, which corresponds to a quantum defect induced heat load of  $6\% \cdot 190 \text{ W} \approx 10 \text{ W}$  for a FOA with 10 W seed and 13 dB gain. In this case, a photodarkening induced heat load of 10 W will double the heat load but only affect the optical efficiency slightly with a reduction in gain of  $<0.5 \text{ dB}$ .

In Fig. 7 the TMI threshold with operation time is plotted for the DMF rod fiber and a 1 m long 285/100 PCF rod fiber experimentally tested in the same high power setup by Johansen et al. in Ref. 11. The TMI threshold is significant higher for the DMF rod fiber compared to the 285/100 PCF rod fiber. The DMF rod fiber efficiently filters out HOMs and allow SM operation even at high output power due to resonant elements in the cladding. The 285/100 rod fiber does not have resonant structures, and therefore as the heat load increases with higher signal power the waveguide mechanisms perturb allowing HOM guidance.<sup>15</sup> TMI is highly dependent on the HOM modal overlap with the active region in the fiber explaining the significant higher TMI threshold for the DMF rod fiber.

#### 4. CONCLUSION

A new improved version of the DMF rod fiber was tested in a high power single pass setup. A maximum extracted stable signal power of 350 W/m was achieved limited by the available pump power and without any observations of TMIs. The slope efficiency was 70 %, and a maximum of 71 % optical to optical efficiency was obtained. A rod fiber operated at high average power experiences a significant heat load that due to the thermo-optical effect will affect the waveguiding mechanisms. In order to observe TMI, the induced absorption of the core material was accelerated by pumping the DMF rod fiber with 200 W of pump power for 2 h, where after the rod fiber was again tested to find the TMI threshold. This procedure was repeated 20 times to thoroughly consider the TMI behavior and threshold degradation. These tests revealed that the TMI threshold decreased with operation time and saturated at roughly 240 W of signal average power. After these tests the fiber was operated as an FOA with 200 W of stable signal average power for about 35 h, the TMI threshold was maintained at roughly 240W.

The overall degradation of TMI threshold was 33 %. However no significant degradation in optical efficiency was observed, indicating that minor induced photodarkening absorption due to color center creation, can have large impact on the generated heat load within the FOA and thereby TMI threshold level.

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